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Accident like the Fukushima unlikely in a country with effective nuclear regulation: Literature review and proposed guidelines

Qiang Wang [a,*], Xi Chen [a], Xu Yi-chong [b]

[a] State Key Laboratory of Desert and Oasis Ecology, Western Research Center for Energy and Eco-Environmental Policy, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
[b] School of Government and International Relations, Griffith University, Brisbane 4111, Australia

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ABSTRACT

The reports from the International Atomic Energy Agency (IAEA) and the Japanese Nuclear and Industrial Safety Agency (NISA) have confirmed that the Fukushima Daiichi nuclear power plant (NPP) survived the initial earthquake impacts, but fell victim to the following tsunami. The 14-m tsunami well exceeded the maximum safety design of 5.7 m. It damaged the pumps, cut off the external power supplies to cool the reactors and spent fuel pool, and directly contributed to the three core meltdowns at the Fukushima Daiichi NPP. These official reports, academic papers, and breaking news also show that five warnings of tsunamis at the Fukushima Daiichi NPP had been ignored by the nuclear operator and regulators since 2000. This article argues that not the natural disaster, but the regulatory failures contributed to the worst nuclear accident since Chernobyl. It explains how the cozy relationship between the government, regulators and nuclear operators, the combined role of NISA as an industry promoter and regulator, and the revolving door between bureaucrats and industries had long undermined the capacity of NISA as a watchdog for nuclear safety. It concludes that upgrading and strengthening a nuclear regulatory system is not optional but imperative to prevent the next core meltdown. Three key recommendations are offered for upgrading nuclear safety regulation.

Contents

* Correspondence to: 818 South Beijing Road, Urumqi, Urumchi 830011, PR China. Tel./fax: +86 899 917 885 420.
E-mail addresses: wang_q@ms.xjb.ac.cn, qiangwang7@gmail.com (Q. Wang).

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1. Introduction

On March 11, 2011, following the mega-earthquake and destructive tsunami on the east coast of Japan, there was a series of equipment malfunction, reactor core meltdowns, and releases of radioactive materials at the Fukushima Daiichi Nuclear Power Plant (NPP). A week later, the Nuclear and Industrial Safety Agency (NISA), the nuclear regulatory body in Japan, declared the Fukushima nuclear accident was at the Level five on INES (International Nuclear and Radiological Event Scale)—the same level of the nuclear accident at Three Mile Island in 1979. On April 12, NISA reassessed the level of accident to the maximum level of seven on INES, putting it on a par with the Chernobyl accident in 1986 [1–4] (see Fig. 1).

One common feature of all three severe nuclear accidents – Three Mile Island NPP in 1979, Chernobyl NPP in 1986, and Fukushima Daiichi NPP in 2011 – is the failure of the cooling system that led to the core meltdown [2,5–8]. One major difference is that the nuclear accident at Fukushima NPP was triggered by a natural disaster—many argue that the accident would not have occurred if there were no earthquake or/and tsunami. This view was emphasized by NISA in a report to the international nuclear authority, IAEA:

> *The (Fukushima) accident, triggered by a natural disaster of an earthquake and tsunami, became a severe accident due to such causes as the losses of power and cooling functions, and that consistent preparation for severe accidents was insufficient* [2].

Many others, including some officials from Japan and officials from other countries [9–13], however, wonder whether the worst nuclear accident since the Chernobyl could have been avoided [14–21]. The then prime minister of Japan, Naoto Kan, was particularly critical of TEPCO in operating and managing the Daiichi NPPs and called it a 'man-made disaster' [22]. What went wrong at Daiichi NPP in March 2011? Could this nuclear accident

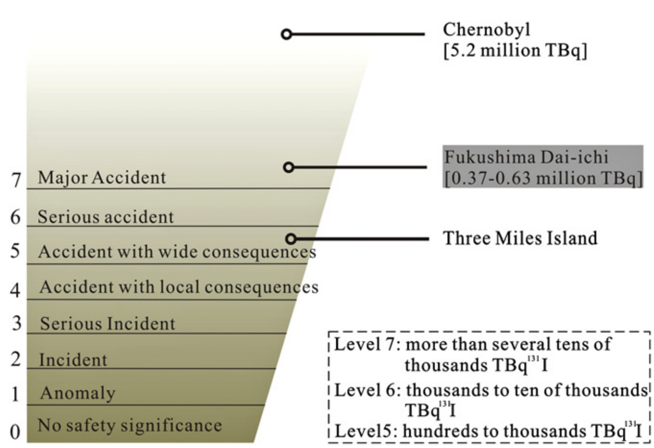


Fig. 1. INES rating on the event in the Fukushima Daiichi NPP.
Source: [4].

have been avoided? What lessons can we draw from the accident? These are the questions the international community has been asking. Yet, few constructive proposals emerged from the IAEA ministerial meeting in June 2011 [23,24], or the United Nations' high-level meeting on nuclear safety and security on September 22, 2011 [25], or the 2012 Seoul Nuclear Security Summit in March 2012 [26].

The nuclear accident at Fukushima Daiichi NPP has had significant impact on nearby communities due to radioactive contamination of land and groundwater, and long-term evacuation of people from their homes, farms, businesses and communities [27–30]. Much wider impacts were also felt. As the public confidence on nuclear energy was shaken, the political fallout from Japan's nuclear crisis reached the world [31–33]. The governments in Germany and Switzerland announced their decisions to phase out nuclear power by 2022 and 2034 respectively, while the Italian government canceled its plan to revive its nuclear energy program. These decisions would not only cost millions of dollars but also left the countries struggling to find alternatives to meet the gap of electricity supplies [34–36].

This article conducts a comprehensive review on the development of the nuclear accident at Fukushima NPP to make sense of the root of the accident and assess the future of nuclear energy development worldwide. After all, according to IAEA, 55 out of 67 reactors under construction in 2010 were in non-OECD countries and will be completed in the next couple of years [37]. In addition, nuclear energy in some countries is still considered an option as (a) it is clean, with zero CO^2 emissions and near zero emissions of greenhouse gas (GHG); (b) it is efficient as its load factor ranges 80–90% rather than 50–60% in thermal power plants, 30–40% for hydro stations, 20–30% for wind or solar generation; (c) it is able to meet base-load demands in areas where population is dense and demand is high while alternative energy sources are scarce; and (d) it represents an advanced 'state of art' technology, from reactor technology to machinery, electrical equipment, basic design and architecture, which has profound industry-wide technology spill-over effects and is able to enhance the productivity of capital, labor and other factors of production in the economy [38–41]. Countries need to learn the lessons from nuclear accidents of the past in order to build an effective system to prevent accidents from taking place in the future.

This article is structured as follows: Section 2 discusses the research method and data collection for this study. Section 3 provides a brief and retrospective discussion of the Fukushima nuclear accident, which was, in our view, triggered not by the earthquake but the destructive tsunami. In Section 4, we propose that since 2000, the Japanese regulators and nuclear operator, TEPCO, had ignored the tsunami warnings at least five times. This conclusion is drawn from a context-specific, longitudinal archival (or historical) analysis on the development of countermeasures against tsunami at the Fukushima Daiichi NPP between 2000 and 2010. In Sections 5 and 6, we examine the nuclear regulatory regime in Japan and the failure of the regulators and TEPCO to take tsunami warnings seriously. We conclude with some policy recommendations for nuclear safety.

2. Research method and data collection

2.1. Research method

A literature review is "*a systematic, explicit, comprehensive and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners*" [42]. It is adopted in this study to provide a broader intellectual background for our analysis. Our study will also follow the process developed by Okoli and Schabram [43] (see Fig. 2).

2.2. Data collection

Since March 2011, a series of official reports, academic papers, and news analyses have been released to analyze the implications of the Fukushima accident for global civilian nuclear programs, to discuss what lessons we can draw from the worst nuclear accident since the Chernobyl, and to propose recommendations for strengthening nuclear safety regulatory systems. Thus, data sources in this review are from the official reports and academic papers, as well as mass media reports (Table 1).

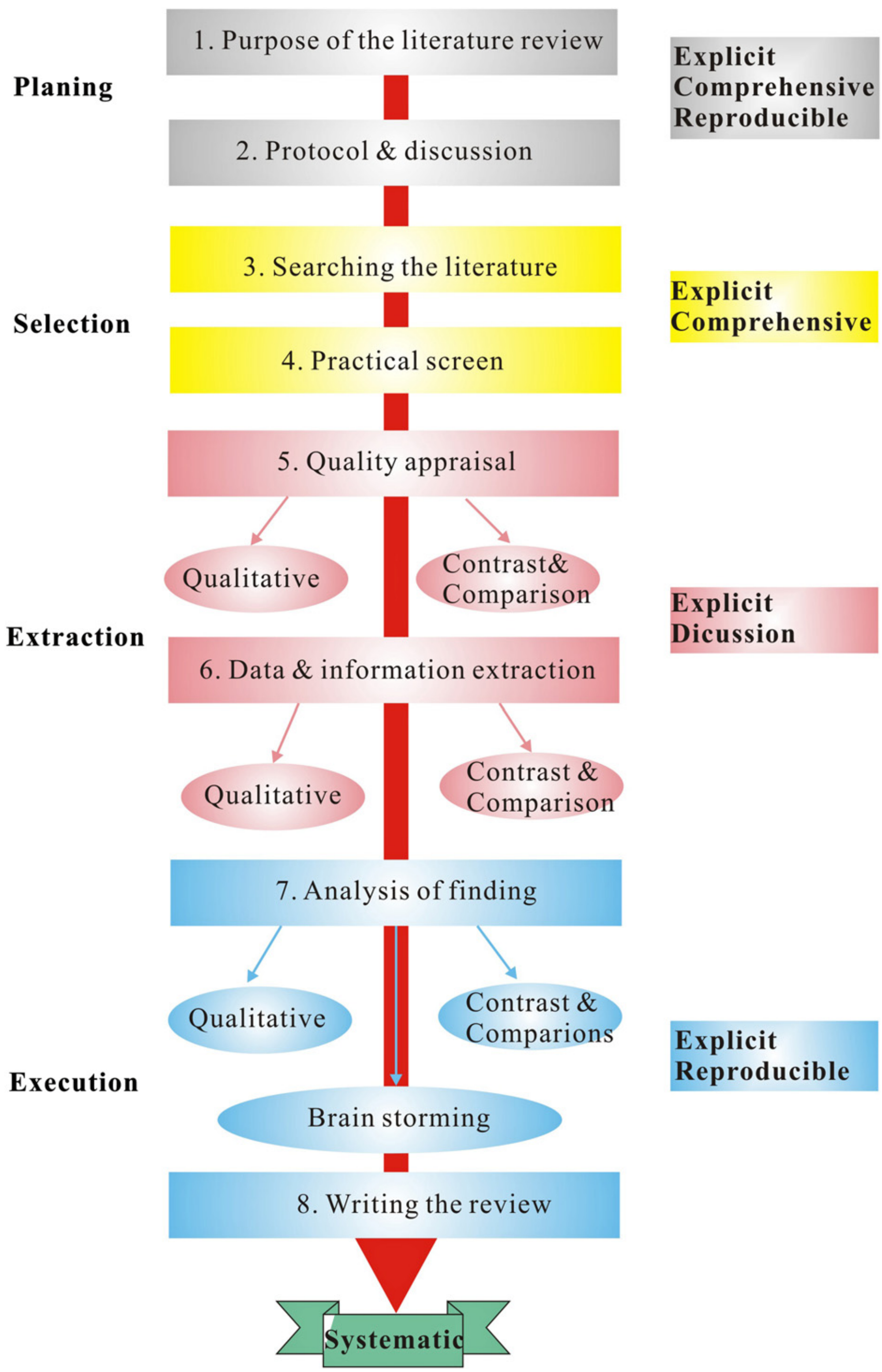


Fig. 2. Research process of systematic literature review and structuring content analysis.
Source: [43].

Table 1
Three main sources of data collection.

Sources	For example
Official reports	1) International level, e.g., IAEA [1,24,44,45], 2) National level, e.g., NISA [2], Japan Atomic Energy Commission (JAEC) [46], U.S. Nuclear Regulatory Commission [47], U.K. Office for Nuclear Regulation [48], and The Investigation Committee on the Accidents at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company [49], 3) Nuclear utilizes, e.g., Tokyo Electric Power Company (TEPCO) [3,50], AREVA [51,52], Westinghouse [53,54].
Academic papers	1) Multi-science magazine. E.g., [8,19,55] in *SCIENCE*; [56–58] in *NATURE*; [59,60] in *Proceedings of the National Academy of Sciences*, 2) Journal, e.g. [14,61–63] in *Bulletin of the Atomic Scientists*, [17,34,64–67] in *Environmental Science & Technology*, [68–71] in *Journal of Nuclear Science and Technology*, [72–74] *Renewable & Sustainable Energy Reviews*, [75] in *Energy Policy*. [76] in Energies.
Mass media	1) International mass media, e.g., [77–82] in *The Wall Street Journal*, [83–87] in *The New York Times*, [11,88–91] *in The Washington Post*, [92–94] in *Guardian*, 2) Japan's mass medium, such as, [95,96] in *The Asahi Shimbun*, [95,97,98] in *The Yomiuri Shimbun*, [99–101] in *The Japan Times*.

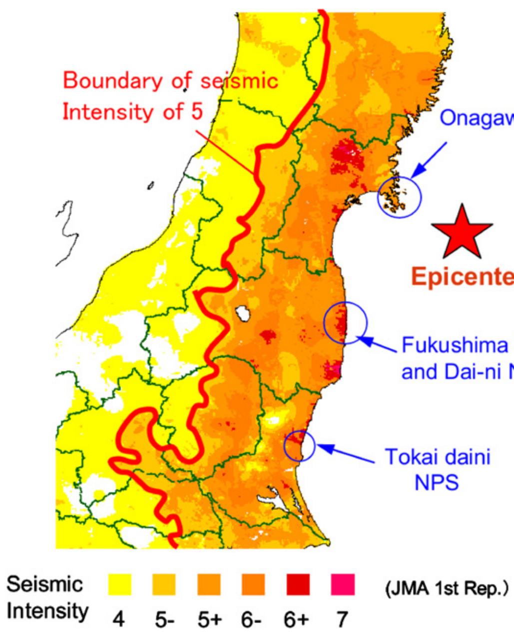


Fig. 3. Map of Japan Meteorological Agency's seismic intensities observed during the main shock.
Source: [2].

3. A brief retrospect: the external factor caused the Fukushima accident

3.1. Natural disaster triggering the nuclear accident

On 11 March 2011, at 2.46 PM local time, a magnitude (M) 9.0 earthquake on the Richter scale hit the northeast coast of Japan. The epicenter was 150 km northeast of the two Fukushima nuclear sites, at a depth of approximately 24 km. Eleven reactors at four sites, Onagawa NPP, Fukushima Daiichi NPP, Fukushima Daini NPP and Tokai Daini NPP (see Fig. 3), that were operating shut down immediately as designed. The Fukushima Daiichi site hosted six reactors: three units shut down automatically and the other three units were undergoing inspection and therefore were not in operation at the time of the earthquake (see Table 2).

The six reactors at the Fukushima Daiichi NPP were boiling water reactors (BWR), designed by General Electric (GE), Hitachi and Toshiba. They started commercial operation between 1971 and 1979 (see Box 1). Units 1–5 were built with Mark I type containment structures. Unit 6 had a Mark II type containment structure [45]. The tsunami that flooded the entire Fukushima Daiichi plant – which had already been cut off from the external power grid by the earthquake – destroyed the back-up electricity system which would be used to power pumps to cool the nuclear fuel rods. The Fukushima Daiichi NPP lost much of its safety related equipment from the tsunami and all off-site and on-site power supplies except for one diesel power generator serving Unit 6. This led to the failure of cooling systems at unit 1, 2 and 3 and that of the spent fuel pools (SFP) of Unit 4. Cooling for other safety related equipment was unavailable or inaccessible either [1–3,50].

Reactors at Fukushima plant, after being shut down, continued generating heat inside even though heat was no longer from the fission process. This was primarily due to the radioactive decay of fission products (decay heat). Cooling was needed to remove this decay heat. Yet, with the failure of cooling systems, the reactor cores in three of the units began to overheat; pressures were increasing; water began to evaporate; and the water level inside the reactor vessels dropped quickly. As the fuel rods were exposed, they started producing hydrogen. As the pressure inside the containment structures increased steadily, heat was vented to the atmosphere. The vented gases and vapor included hydrogen, produced by the exothermic interaction of the fuel's very hot zirconium cladding with water. The hydrogen subsequently escaped from the reactors and primary containment vessels where it reacted with oxygen, resulting in explosions at unit 1 reactor on 12 March and unit 3 on 14 March that damaged the outer buildings. On 15 March, the pressure suppression chamber of unit 2 under the actual reactor ruptured, releasing significant radioactivity. With the loss of the isolation condenser, reactor core isolation cooling, and the high pressure coolant injection systems, a decision was made to inject seawater into the reactor pressure vessels [2,46]. Even with these efforts significant fuel melting occurred at units 1, 2 and 3.

3.2. The Fukushima Daiichi NPP survived earthquake, only to fall victim to a tsunami

Based on the findings of the official reports by the IAEA, NISA, TEPCO and TEPCO's Investigation Committee on the Accident at the Fukushima Nuclear Power Stations, it is clear that the earthquake was not a major cause of the Fukushima nuclear accident. TEPCO President Masataka Shimizu confirmed this in a statement issued on March 18, 2011:

> *The accident was caused by the violence of nature – a tsunami caused by an unprecedented earthquake – and it is regrettable the crisis has escalated to such an extreme state of affairs*

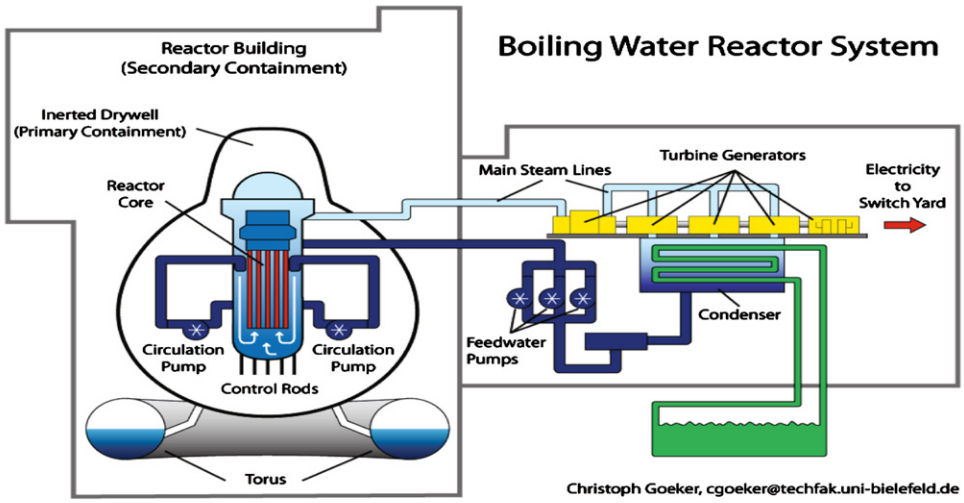


Fig. 4. Schematic of a boiling water reactor.
Sources: [105].

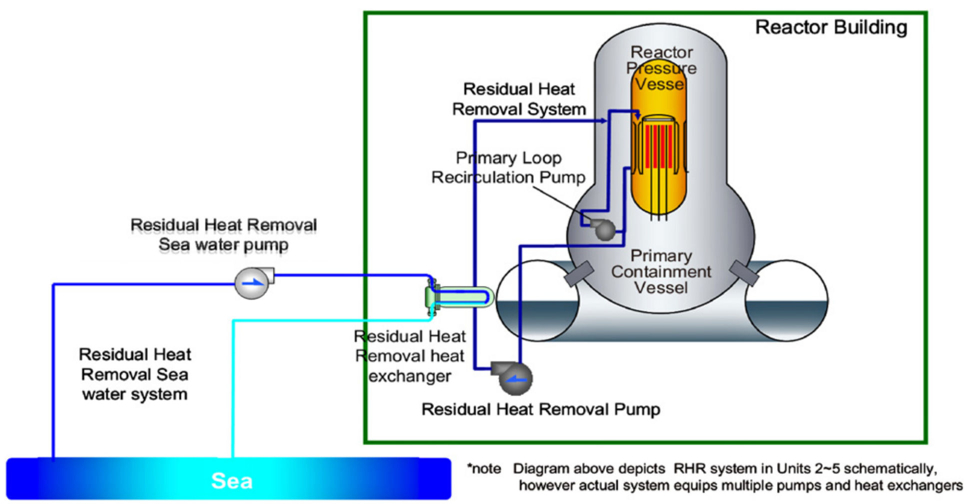


Fig. 5. Core cooling system under normal shutdown.
Source: [50].

Table 2
Status of nuclear power plants affected by the 2011 off the pacific coast of Tohoku earthquake.
Source: [1].

Nuclear power plant	Unit	Type		Capacity (Mw)	Status		
		CV[a] type	Safety system		Before earthquake	After earthquake	After tsunami
Onagawa	1	Mark I	BWR-4	524	Operating	Automatic scram	Cold shutdown
	2	Mark I	BWR-5	825	Reactor start	Automatic scram	Cold shutdown
	3	Mark I	BWR-5	825	Operating	Automatic scram	Cold shutdown
Fukushima Daiichi	1	Mark I	BWR-3	460	Operating	Automatic scram	Loss of cooling
	2	Mark I	BWR-4	784	Operating	Automatic scram	Loss of cooling
	3	Mark I	BWR-4	784	Operating	Automatic scram	Loss of cooling
	4	Mark I	BWR-4	784	Outage	Cold shutdown	Loss of SFP[b] cooling
	5	Mark I	BWR-4	784	Outage	Cold shutdown	Cold shutdown
	6	Mark II	BWR-5	1100	Outage	Cold shutdown	Cold shutdown
Fukushima Daini	1	Mark II	BWR-5	1100	Operating	Automatic scram	Cold shutdown
	2	Mark II R	BWR-5	1100	Operating	Automatic scram	Cold shutdown
	3	Mark II R	BWR-5	1100	Operating	Automatic scram	Cold shutdown
	4	Mark II R	BWR-5	1100	Operating	Automatic scram	Cold shutdown
Tokai Daini		Mark II	BWR-5	1100	Operating	Automatic scram	Cold shutdown

[a] Containment vessel.
[b] Spent fuel pool.

Box 1–Boiling water reactor (BWR)

Part I. The boiling water reactor uses demineralized water as a coolant and neutron moderator. Inside the BWR vessel, a steam water mixture is produced when pure water moves upward through the core absorbing heat. The major difference in the operation of a BWR from other models of reactor is the steam void formation in the core. The steam–water mixture leaves the top of the core and enters the two stages of moisture separation, where water droplets are removed before the steam is allowed to enter the steam line. The steam line, in turn, directs the steam to the main turbine causing it and the attached electrical generator to rotate. The unused steam is exhausted to the condenser where it is condensed into water. The resulting water is pumped out of the condenser with a series of pumps and back to the reactor vessel. The recirculation pumps and jet pumps allow the operator to vary coolant flow through the core and change reactor power. BWRs typically operate at a water/steam temperature of approximately 300 °C and a pressure of around 75 times atmospheric pressure (see Fig. 4). All Fukushima's condensers were cooled by seawater passing through the secondary side. Once condensed, the water is pumped back into the reactor vessel, starting the cycle all over again [48,102,103]. Prior to the nuclear accident at the Fukushima Daiichi NPP, the core damage frequency of the reactor was estimated to be between 10^{-4} and 10^{-7}, i.e., one core damage accident per every 10,000 to 10,000,000 reactor years [104].

Part II. With core cooling system of BWR under normal shutdown, (i) nuclear fuels continue to generate decay heat even after stop of fission by control rod insertion; (ii) ''Residual Heat Removal System (RHR)'' pumps circulate reactor coolant and remove heat by sea water through heat exchanger in ''Residual Heat Removal Sea water System''; and (iii) this will enable fuels in reactors to be kept in stabilized cooling state (under 65 °C). (See Fig. 5)

To TEPCO, the Fukushima nuclear accident was due entirely to the destructive tsunami [106]. As shown in Fig. 6, the Fukushima Daiichi NPP survived March 11th earthquake intact, only fell victim to a tsunami that wiped out its backup power generators [1,2].

Although the mega-earthquake cut off the external power supply (see Fig. 7), it did not destroy the systems, equipment or devices important for nuclear safety at the Fukushima Daiichi NPP [2,3]. A safe automatic emergency shutdown of nuclear reactors took place within seconds of the earthquake. Control rods were fully inserted within seconds too and all 13 diesel generators started when tremors disconnected the grid connection, as designed. Instrumentation was working correctly, so were the cooling systems. Shocks recorded at the site were around the maximum that the plant had been designed to withstand and walk-down checks by plant staff showed no indication of significant damage to coolant systems [3,49,107].

Approximately 40 min after the *M*9 earthquake, the first major tsunami arrived at 15:27 local time, and the second one came at 15:35. This was followed by multiple additional waves. The run-up height of the tsunami was approximately O.P. (Base level of Onahama Port construction)+14.5 m, which substantially exceeded the height under the design of construction permit (5.7 m) at the Fukushima Daiichi NPP. Inundation depth was approximately 4 to 5 m in most of the ocean-side of the main building compound where reactor buildings and turbine buildings were located. The inundated areas covered most of the ocean-side area (height of site: O.P.+4 m) and the main building area. As a result, almost the entire site of Fukushima Daiichi NPP was submerged by a series of tsunami waves (see Fig. 8).

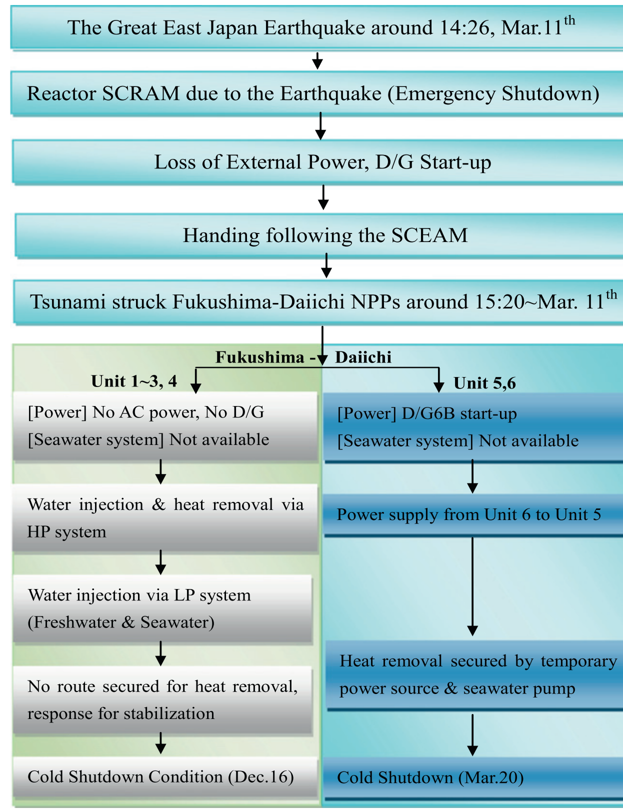


Fig. 6. Progress towards cold shutdown status in each unit at the Fukushima Daiichi nuclear power plant.
Source: [50].

The tsunami after the earthquake destroyed the emergency pump equipment for all units except for one diesel generator serving unit 6. This prevented residual heat (decay heat) from being removed from the reactor. The diesel generator for unit 6 was then used for both unit 5 and 6. The flood also destroyed some 36 other distribution panels. Without power supplies, all motor-operated facilities (safety systems, water injection and cooling equipment, etc.) at unit 1 to 5 could not function and motor-operated valves at the magnetically controlled reactor (MCR) stopped operation. At units 1, 2, and 4, without Direct Current (DC), all monitoring instruments in the MCR became unavailable. The plant status could no longer be monitored. At units 3 and 5, where DC power was available, the plant condition was measured and monitored by the battery levels. Safety relief valve (SRV) for reactor depressurization and solenoid valves for controlling air-operated vent valves for the primary containment vessel also became inoperable. In sum, without power supply, it was impossible to remove heat from the reactor, to operate all electrical equipment, including MCRs that lost their monitoring and operating functions, or to communicate with workers in the field (see Fig. 9) [3]. When the meltdown occurred at units 1, 2 and 3, a disaster could not be avoided.

4. Can tsunami risk for nuclear power plants be predicted and prevented?

As discussed above, the 14-m tsunami directly caused a loss of power supply from emergency power backup systems for the cooling systems and, consequently, three core meltdowns at the Fukushima Daiichi NPP happened. In this sense, it is important to ask whether the tsunami should and could have been

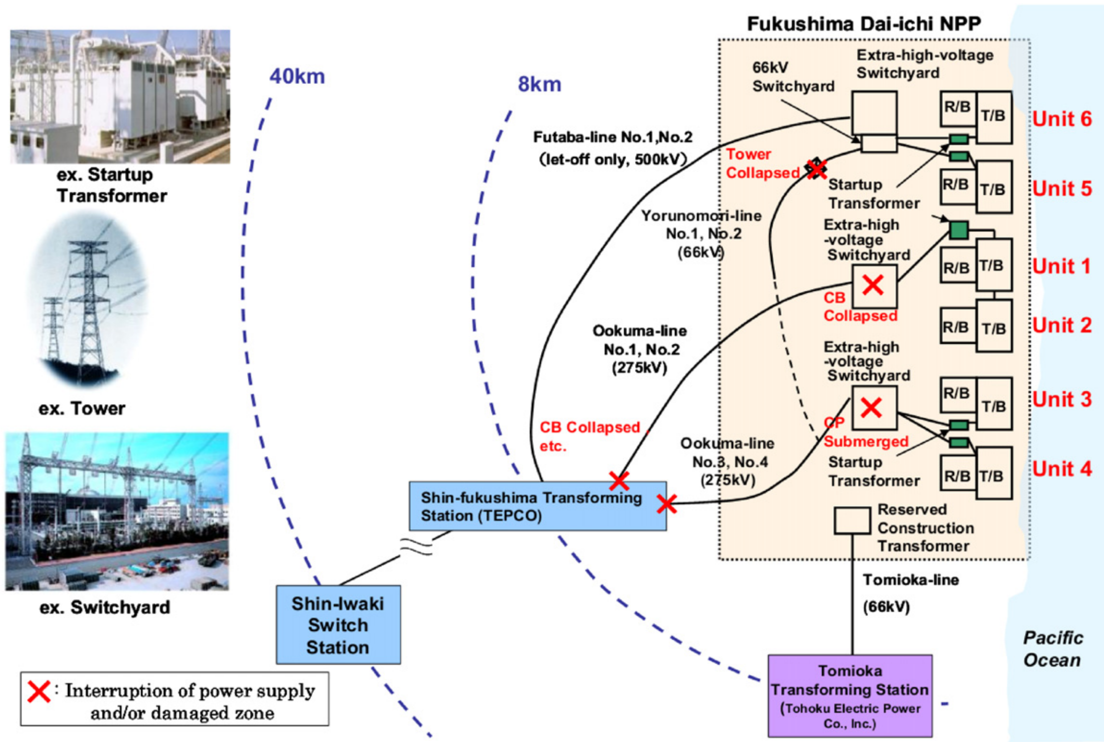


Fig. 7. Damage of external power supply systems for the Fukushima Daiichi NPP.
Source: [2].

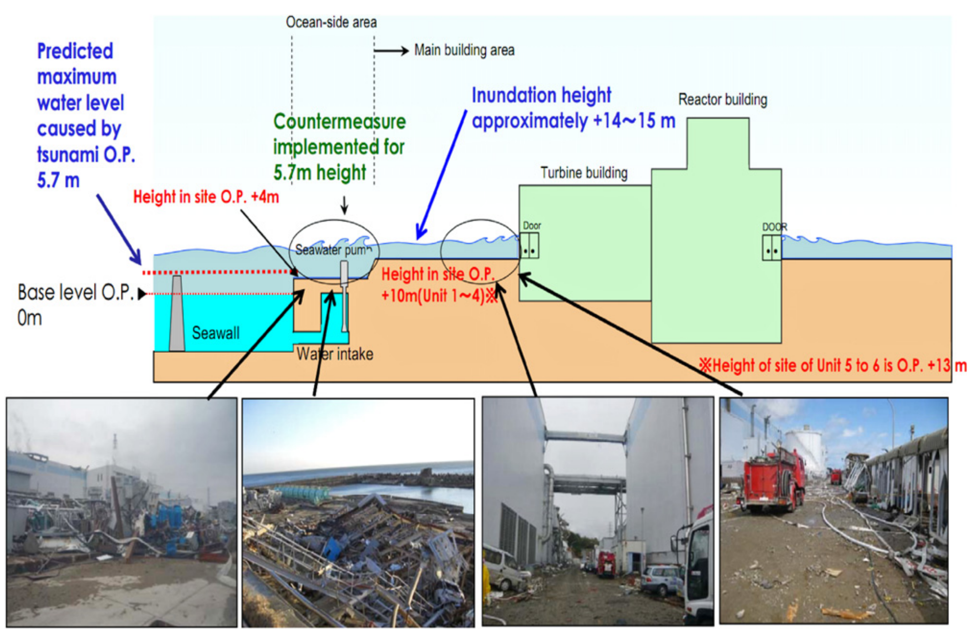


Fig. 8. Damage of Fukushima Daiichi NPP due to the tsunami.
Sources: [108].

calculated as a decisive factor for risk assessment of reactor meltdown at the Fukushima Daiichi NPP. Could a tsunami at the Fukushima Daiichi NPP have been expected? Was it possible to put in place measures to prevent potential disaster as the result of a tsunami?

Given that archival/historical materials are useful to reproduce decision-making processes [109], we conducted context-specific, longitudinal archival analysis of the development of the tsunami design at the Fukushima Daiichi NPP between the 1960s and 2010. These archival/historical materials show that (i) a seawall designed with a height of 3.1 m at the Fukushima Daiichi NPP in the 1960s might arguably be said to have been reasonable, but (ii) TEPCO had missed many opportunities to upgrade countermeasures for tsunami risks since all the reactors went into operation between 1971 and 1979, especially in the past decade. After 2000, five warnings about tsunamis risk at the Fukushima Daiichi NPP were issued and then ignored by TEPCO and Japan's nuclear regulators.

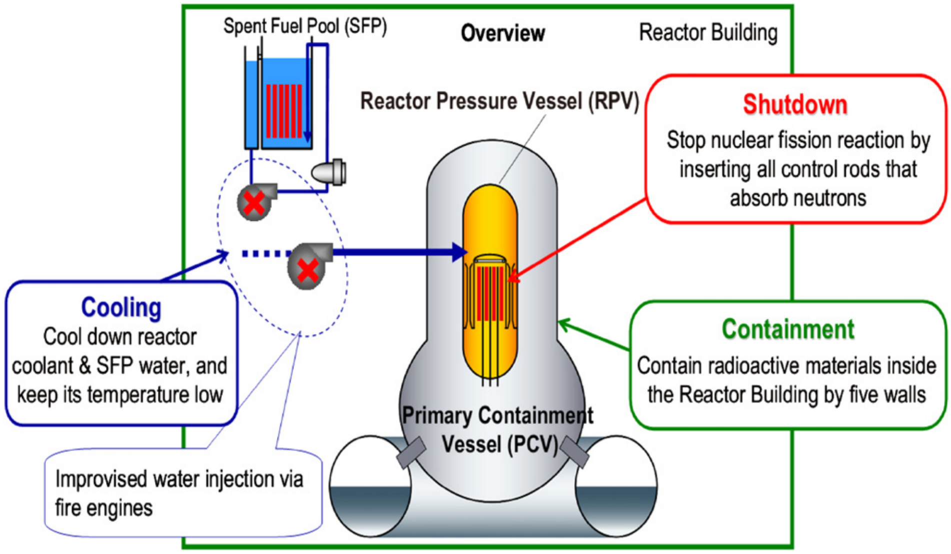


Fig. 9. Tsunami impacts on safety function at Fukushima Daiichi NPP. *Notes*: The process of tsunami impact on safety function: (a) Nuclear fission chain reaction was stopped by automatic shutdown with all control rods inserted at the same time of the earthquake. (b) Off-site power was lost due to the impact of the earthquake, etc. and emergency generator started up. However emergency power became unavailable due to flooding by the tsunami except for Unit 6. (c) Finally the "Cooling" function for the reactors and spent fuel pools of Units 1 to 4 were lost due to the loss of AC power supply and seawater systems, etc. caused by the tsunami. (d) Given that high level contaminated water has been found in turbine buildings, "Containment" function is presumed to be impaired.
Source: [50].

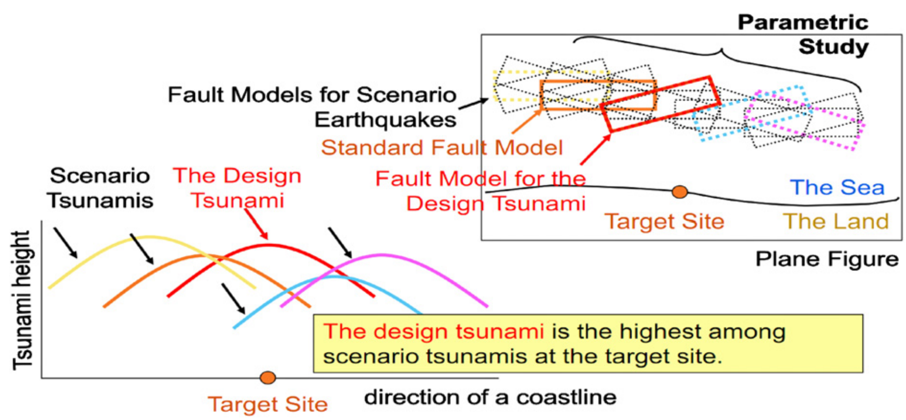


Fig. 10. Concept diagrams of the design tsunami and related terms.
Source: [110,111].

4.1. Tsunami-resistance design at the construction of the Fukushima Daiichi NPP

The safety standards designed to withstand specified tsunami were adopted by the Japanese Society of Civil Engineers in 2002 [110]. The standards were determined by a numerical simulation based on information of the maximum historical tsunami and the greatest impacts of tsunami-induced submarine activity (see Fig. 10).

Construction of the six reactors at the Fukushima Daiichi NPP began in 1967, when relatively little was known about tsunami hazards [112]. Table 3 provides the historical tsunami data between 800 and 1965 for the Tohoku region. As shown, when the Fukushima Daiichi NPP was designed and built in the mid-1960s, no large tsunamis were known to have hit that particular section of the coast [16]. Without historical precedent, it was difficult to decide the standards for potential tsunami. In addition, safety assessments for tsunami risks at nuclear power plants were then based on "*the Guideline about Safety Design for Light Water Nuclear Power Generating Facilities*" issued by the Nuclear Safety Commission of Japan (NSC). This guideline had not stipulated specifically countermeasures against tsunami. It only stated that "(the effect by) *tsunami should be considered in design*", but did not say "the design tsunami should be determined by numerical simulation" [113]. Hence, a seawall with a height of 3.1 m at the Fukushima Daiichi NPP in 1970s might be arguably said to have been reasonable [3,16].

4.2. The 2002 Re-evaluation design heights of seawall

In 2002, a standard assessment of tsunami risks for nuclear facilities, "*Tsunami Assessment Method for Nuclear Power Plants*", was issued by the Japan Society of Civil Engineers [110]. Its proposals for the evaluation of the tsunami risks at nuclear power plants in Japan are shown in Fig. 11.

Based on the guideline issued by the JSCE, TEPCO re-evaluated the height of the seawall at the Fukushima Daiichi NPP in 2002. It assessed and reported that the maximum height of future tsunamis that could impact Fukushima Daiichi NPP would not exceed 5.7 m (Maximum water level = 4.4 m + O.P. (Base level of Onahama Port construction) + 1.3 m = O.P. + 5.7; Minimum water level = −3.6 m − O.P 0.0 m = O.P. − 3.6 m) [114].

Table 3
Basic parameters of the largest historical tsunamis in the Tohoku region.
Source: [16].

Date	Magnitude	Maximum (meter)	Fatalities	Comments
869, July 3 (Jogan)	$M>8.5$	Unknown	>1000	Giant earthquake in Tohoku region. Sendai plain was flooded up to four kilometers inland.
1611, Feb. 2 (Keicho)	$M>8.0$	25	>5000	Strong earthquake in Sanriku. Entire northeast coast of Honshu Island was flooded by tsunami.
1896, June 15	$M=7.6$	38	27, 122	Quiet earthquake generated a destructive tsunami.
1933, March 2	$M_s=8.1$	28	3000	Strong earthquake with destructive tsunami. In Sanriku more than 6000 houses were destroyed.
1960, May 24	$M_w=9.5$	5–7	142	Giant earthquake in Chile generated trans- Pacific tsunami, which destroyed more than 10,000 houses in Japan.
1968, May 16	$M_w=8.3$	4–5	0	Strong earthquake, but resulting tsunami was moderate and resulted in no fatalities.

M=macroseismic magnitude (i.e., estimated from damage reports); M_s=surface-wave magnitude; M_w=moment-magnitude. Fatalitydata for the 2011 earthquake are from the National Police Agency home page, as of August 27, 2011.

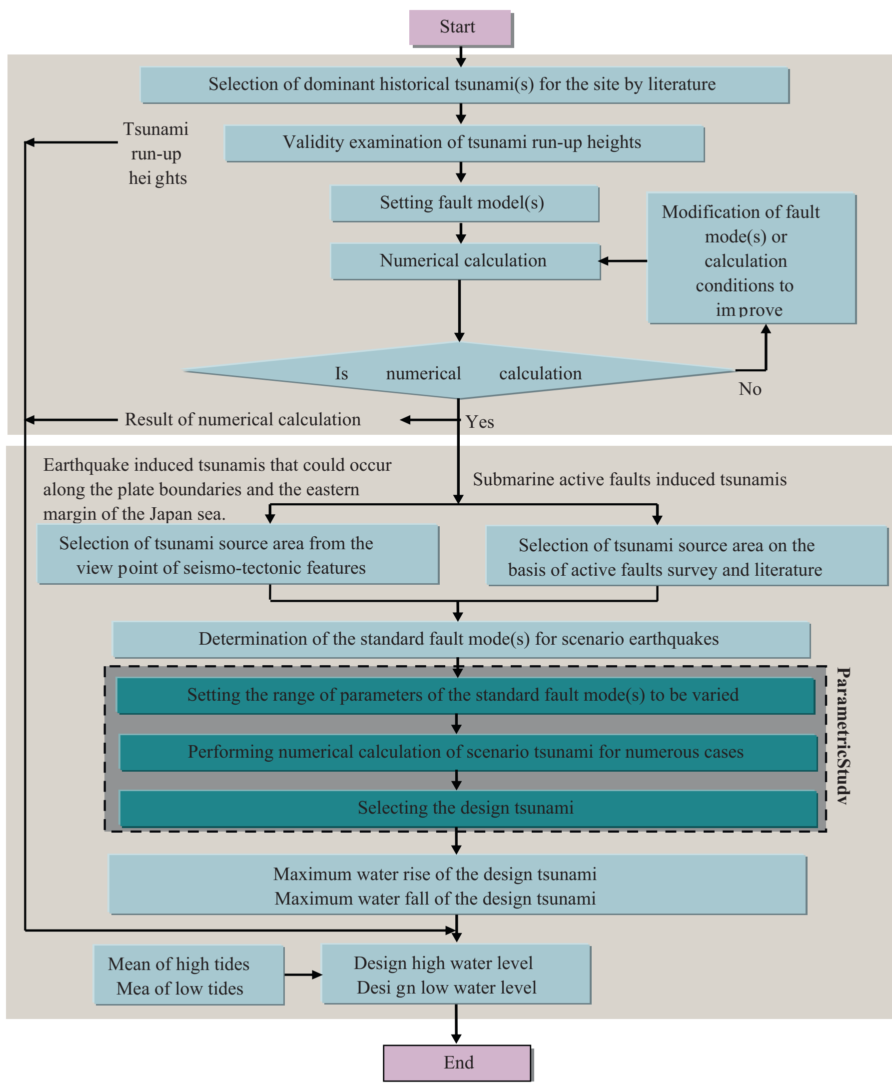


Fig. 11. Flowchart for the assessment of the design tsunami. *Notes*: (1) Tsunami source for the design tsunami. Among the various possible scenario tsunamis for each area, the one causing the maximum water rise and fall to the target site is selected as the "design tsunami." The design water level is defined as the sum of the "design tsunami" and an appropriate tidal condition [110]. (2) A consideration policy with regard to the uncertainties of scenario tsunamis. In order to account for the uncertainties regarding a tsunami source in the model, a large number of numerical calculations are carried out under various conditions within a reasonable range. This is referred to as a "parametric study." Each results of the parametric study are termed as scenario tsunamis. For the model to the target site, the tsunami causing the greatest damage to the target site is selected among the scenario tsunamis [110]. (3) Method for verifying the design tsunami. The design tsunami is verified by using the following criteria. The design tsunami height exceeds all the recorded and calculated historical tsunami heights at the target site. In the vicinity of the target site, the envelope of the scenario tsunami heights exceeds all the recorded and calculated historical tsunami heights [110]. (4) Method for verifying the assessment procedure based on historical tsunamis. Before the abovementioned steps are carried out, a numerical calculation system is verified by performing numerical calculations on historical tsunamis [110].
Source: [110].

This evaluation did not take into account any of the data or assumptions about earthquake size or location, both of which are vital to determine whether the calculations would make sense [115]. Moreover, TEPCO's assessment was limited to the areas where few tsunamis occurred in the past. No model was available for the "gap" beneath the seabed close to the Japan Trench, or far off the Fukushima Prefecture coast, where no tsunami was known to have originated [95].

TEPCO also overlooked the tsunami risks warning from the government. The Headquarters for Earthquake Research Promotion, a government agency, warned in July 2002 that tsunami could originate close to the trench anywhere between the Sanriku coast of the Tohoku region and the Boso Peninsula in Chiba Prefecture. This included a potential tsunami below the seabed off Fukushima Prefecture. TEPCO, however, took virtually no action. Incorporating the ideas of the earthquake research into a tsunami model would involve major challenges of dealing with uncertainties in the properties of the tsunami, including its source size [95]. Furthermore, NISA neither demanded the information nor scrutinized the TEPCO's re-evaluation proposal. Instead, NISA approved the design of the seawall of the Fukushima Daiichi NPP to withstand a sea wave up to 5.7 m [116,117]. If NISA had looked at it more seriously, it would have noticed that 22 of the 35 people on the committee that wrote the re-evaluation proposals had strong ties to the nuclear power industry. Among them, three were from TEPCO and one was from its affiliated utility; 13 were from Japan's other electricity companies [88]. The proposal for tsunami countermeasures at the Fukushima Daiichi NPP in 2002 therefore reflected more the demand of the nuclear industry than the nuclear safety concerns or requirements. On March 11, 2011, the 14-m-high tsunami waves overwhelmed the protective seawall (5.7 m) and crippled the Fukushima Daiichi NPP.

4.3. The 2004 Sumatra earthquake and the 2006 revised safety guideline

In December 2004, tsunamis following the *M*9.2 Sumatra earthquake caused more than 200,000 fatalities [118]. Geologically, the *M*9.2 Sumatra earthquake indicates that mega-quakes can occur not only in certain types of subduction zone, but also in regions, such as Sumatra and Tohoku. Before the Sumatra earthquake, some geoscientists had thought that mega-quakes could not occur in the regions such as Sumatra and Tohoku [118–121]. The *M*9.2 Sumatra earthquake also shows that large tsunamis can propagate substantial and damaging wave energy to distant coasts, through a combination of source focusing and topographic waveguides. Local resonant effects may strongly amplify the arriving waves [122].

The tsunami following the Sumatra earthquake reached the east coast of India and affected the Kalpakkam NPP in Tamil Nadu province. When unusual water levels were detected in the cooling water intake, the plant shut down automatically. It was restarted six days later. In light of the Kalpakkam nuclear incident, in August 2005, IAEA organized the *International Workshop on External Flooding Hazards at Nuclear Power Plant Sites* in Kalpakkam, India, to examine the potential impact of tsunamis on nuclear reactors and to discuss whether international safety standards for nuclear plants in tsunami-risk areas need to be upgraded [123]. IAEA then proposed that most of the world's 430 nuclear power plants should have stronger protection against flooding, especially the nuclear facilities in Japan and the United States that sit along the tsunami-prone Pacific Rim [124].

After the IAEA's international workshop, in 2006, NSC in Japan revised the *Seismic Safety Examination Guidelines related to reactor facilities for power generation* that was adopted in 1978 ("Old Seismic Guidelines" in Fig. 12) by its predecessor, the Atomic Energy Commission ("New Seismic Guidelines" in Fig. 12). The new Seismic Guidelines recognized tsunamis as an accompanying phenomenon of earthquakes. NSC urged electricity companies to take into consideration any active fault-lines that had slipped since the late Pleistocene era (120,000 to 130,000 years ago)) [95,125,126]. Again, TEPCO did not take the advice; nor did it upgrade the countermeasures against tsunami at Fukushima Daiichi NPP, as suggested in the 2006 revised guideline [16,127].

4.4. The 2007 Kashiwazaki–Kariwa nuclear incident

The *M*6.8 Niigata Chuetsu-Oki earthquake on July 16, 2007, with its epicenter only 16 km from TEPCO's Kashiwazaki Kariwa NPP, exceeded the designed level for the seismic impacts on the plant (this nuclear facility was designed to withstand a *M*6.5 earthquake). Three reactors were not in operation at the time. Another four reactors shut down automatically and the cooling system started working subsequently [128,129].

Based on this development at the Kashiwazaki Kariwa NPP, IAEA suggested all nuclear operators should re-evaluate seismic safety standards, using updated criteria and methods. In particular, detailed on-land and offshore geophysical investigations should be taken to define the new seismic input to the plants. It also proposed that these investigations should address the issue of the potential existence of active faults underneath the site while taking into consideration the possibility that the long-term operation of components could be affected by hidden damage from the earthquake [44,130].

Following the IAEA's suggestion, NISA required nuclear operators in Japan to look back 130,000 years, rather than the previous 50,000 years, to find evidence that it was seismically active [129]. The design-basis ground motion must be formulated based on the latest knowledge. To formulate a new design-basis ground motion, the knowledge obtained through this earthquake must be clarified and reflected. In addition, nuclear operators should conduct a retroactive re-evaluation of the seismic safety of existing nuclear power plants, and the results must be properly reflected when reviewing the earthquake resistance of other nuclear power facilities in addition to the Kashiwazaki–Kariwa ones [131].

TEPCO spent 100 billion yen (US $1.3 billion) on reinforcing the facility against earthquakes at Kashiwazaki Kariwa NPP, which then passed NISA's screening according to the revised guidelines, including tsunami preparedness, and it was given the green light to resume operations (see Fig. 13). TEPCO, however, did not conduct an assessment on tsunami resistance and preparedness at the Fukushima Daiichi NPP [95].

4.5. The 2008 TEPCO prediction

In 2008, TEPCO predicted that a tsunami with high waves of more than 10 m could strike the Fukushima Daiichi NPP. It made this prediction based on a potential earthquake of the same magnitude as the Meiji Sanriku Earthquake *M*8.3 in 1896, which would be followed by a tsunami with waves as high as 8.4–10.2 m. It also predicted that the water would move inland and could reach a height of 15.7 m above sea level at units 1 to 4 reactors, and 13.7 m at units 5 and 6 reactors at Fukushima Daiichi NPP. TEPCO calculated the potential impacts of earthquake and tsunami based on the research findings of the National Institute of Industrial Science and Technology on the 869 Jogan Earthquake (*M*8.6). It showed that a tsunami 8.7–9.2 m high could hit the Fukushima Daiichi NPP's water-intake facility. The predicted height of the tsunami inundation heights in 2008 were all in excess of the maximum 5.7 m in the safety design [49,98,132].

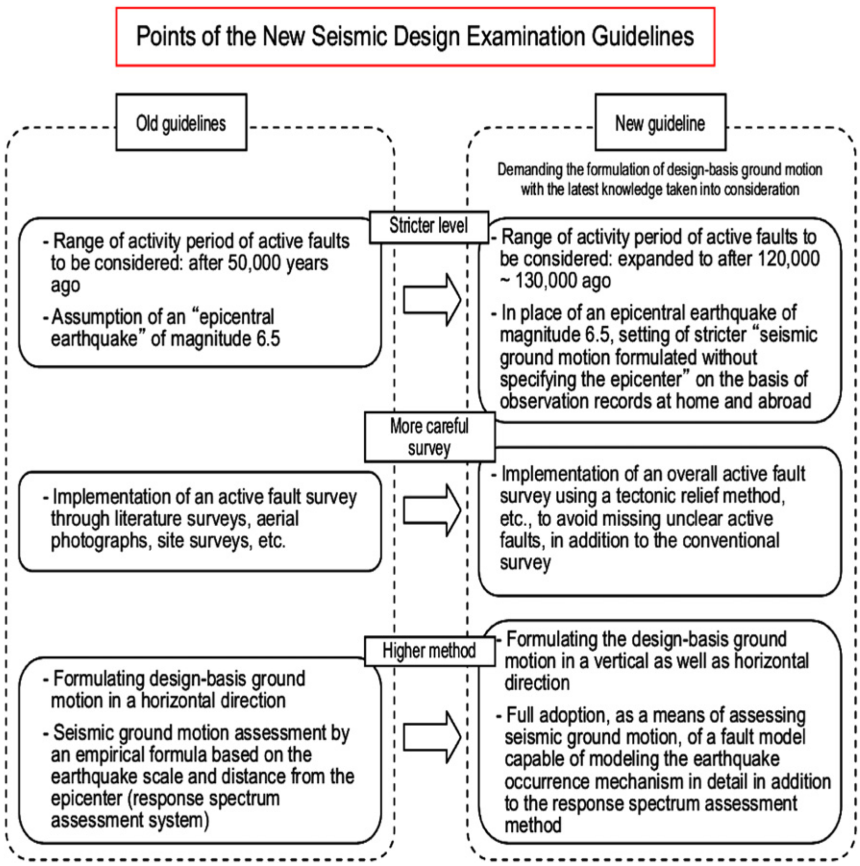


Fig. 12. Comparison between the seismic guide in 1978 and revised seismic guide in 2006.
Source: [105].

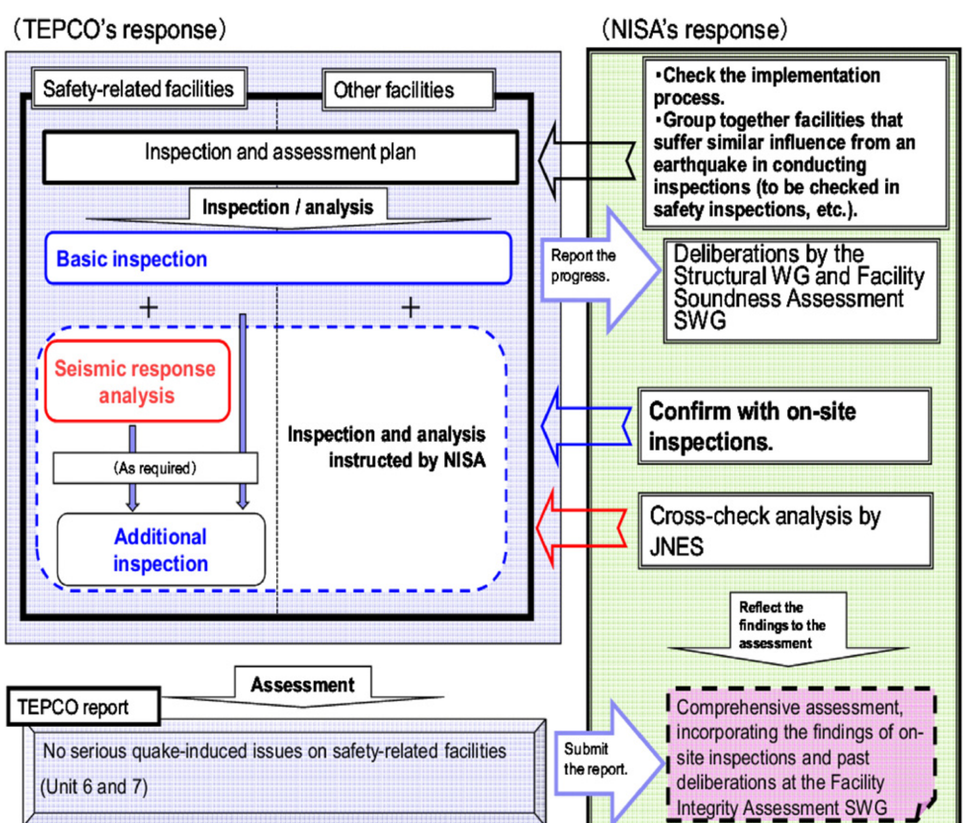


Fig. 13. TEPCO's integrity assessment work checked by NISA.
Source: [131].

The experts at TEPCO who had conducted the research reported their assessments to Sakae Muto, an operating officer and deputy head in charge of nuclear plant locations at the headquarters. The findings were then reported to Ichiro Takekuro, then TEPCO executive vice president in charge of nuclear power plants. The management of TEPCO, however, did not take the predictions seriously nor incorporate into its 2008 assessment countermeasures against tsunamis at the Fukushima Daiichi NPP. Instead, the management maintained its tsunami risk mitigation measures on the premise of a tsunami 5.7 m high at the Fukushima Daiichi NPP. Why did not TEPCO upgrade its safety countermeasures based on the 2008 assessment? The management later argued that the findings of the research were drawn from the cases that had happened somewhere else other than Fukushima. These figures "were the result of an extreme simulation that imagined the recurrence of the Meiji Sanriku Earthquake off Fukushima Prefecture," defended Junichi Matsumoto, acting head in charge of nuclear plant locations at the headquarters, at a press conference on August 24, 2011. "We judged that releasing the data was unnecessary and we didn't need to reflect the results in our facilities or management" [95,98].

4.6. Hearings in 2009

In 2008, NISA organized a panel of engineers, geologists and seismologists to review the safeguard and safety standards for all nuclear power plants and then make suggestions for necessary revisions. These experts were selected by NISA. TEPCO officials attended the meetings, but were not on the panel. The Panel on the Fukushima Daiichi NPP wrapped up its review on June 24, 2009 and presented its findings to a larger working group of 40, which included just two tsunami experts. It was there that Yukinobu Okamura, a senior geologist at a government-affiliated research laboratory, first raised the issue that a tsunami could be as risky as an earthquake. Only in recent years, based on evidence collected in geological layers and sediment deposits, had a handful of Japan's tsunami experts concluded that a tsunami disaster was more than imaginary. Okamura was one of them. He told the panel, a massive quake struck off the coast of Sendai, northeastern Japan, in A.D. 869, sending a tsunami wave more than two miles inland. He then asked a TEPCO official at the meeting, "research results are out, but there is no mention of [tsunami] here, and I would like to ask why," according to a transcript of the meetings [89].

TEPCO officials defended their position and downplayed tsunami risks, saying that the guidelines for Fukushima had already factored in a far more recent earthquake, measured 7.9 magnitude. When Okamura pressed on and pointed out that the Jogan earthquake of 869 knocked down a castle, TEPCO officials dismissed its relevance, "As you know, it is a historic earthquake." "I don't know how that conclusion can be drawn," Okamura persisted. "To have no mention of that, to me, leaves me unsatisfied." According to the meeting transcript, a NISA official ended the debate by promising to follow it up. At the next meeting, however, the working group approved the Daiichi safety report that declared the complex's safeguards were sufficient [89].

4.7. Delayed actions

On March 11, 2011, the 14-m tsunami destroyed the backup generators, stopping cooling of fuel rods at the Fukushima Daiichi NPP. The fuel rods at the unit 1 reactor began to heat up right away. Efforts should have been made immediately to cool and depressurize the crippled unit 1 reactor. However, critical actions were delayed (Kushida 2012). There was no water injection for 14 h and 9 min, after the total loss of AC power at 15:37 on 11 March until the start of water injections at 5:46 the next day (see Fig. 14). This delay partly led to the total meltdown at unit 1 reactor and the hydrogen explosion which doomed unit 2, 3 reactors [10,17,70,133].

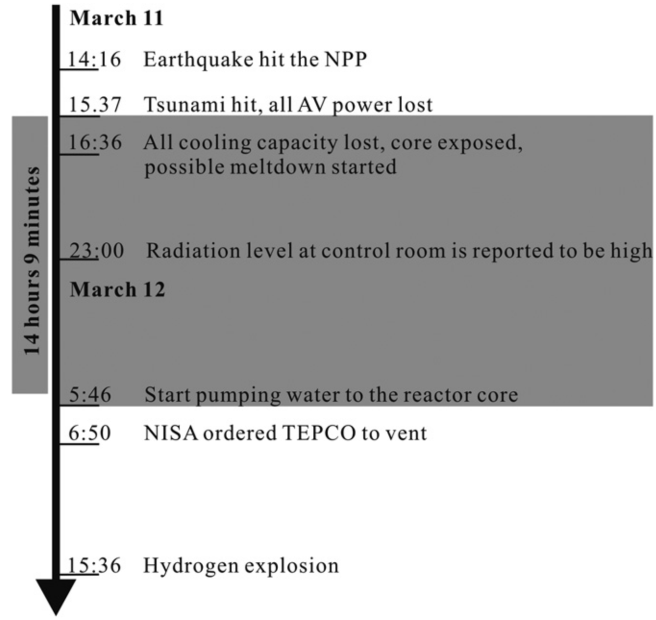


Fig. 14. Chronology from the occurrence of the accident to the emergency measures taken.
Sources: [2,3].

On September 15, 2011, researchers at the Japan Atomic Energy Agency reported the finding based on a computer simulation of the accident at the plant's unit 2 reactors, where a hydrogen explosion on March 15th caused the release and spread of massive amounts of radioactive substances. The simulation suggested that if water injection had been done 4 hearlier, it could have prevented the meltdown by lowering the temperature of the fuel pool before it reached 1200 °C, destroying the fuel's container. Group leader Masashi Hirano said the damage to the fuel could have been avoided and he wondered why TEPCO did not start injecting water earlier despite difficulties [133]. Bernard Bigot, chief of the French atomic energy commission, confirmed this view.

On October 9, 2011, during a Q&A session after delivering a speech in Tokyo, Bigot said, "*There was a need to inject seawater from outside within 6 to 12 h…and I think it was physically possible to avoid (the accident), although I can say this only now*" [10].

These findings contradict TEPCO's assertions that the size of the March 11 tsunami was "unpredictable." In the authors' view, tsunami risks for the Fukushima Daiichi NPP could have been assessed, predicted and even prevented. Indeed, TEPCO submitted an assessment to the NISA on tsunami risks on March 7, 2011 four days before the earthquake triggered the deadly tsunami. This assessment, released in October 2011, stated that preventative measures for tsunami were still "under consideration" and that the official tsunami height predicted would be revised "at an appropriate time." The targeted date for the revisions was October 2012 [95,134,135]. In sum, warning of a potential tsunami at the Fukushima Daiichi NPP was made; tsunami risks were predicated, and probably could have been prevented. Yet, nuclear regulators and TEPCO missed many opportunities to upgrade countermeasures against tsunami risks.

5. Triple questions why these tsunami warnings were overlooked

First, why were tsunami warnings overlooked in a modern, highly sensitive, tsunami-conscious country? Japan has developed

the world's densest seismometer networks and the most extensive earthquake and tsunami early-warning systems [136–138]. In the late 1950s, simple seismometers were installed for a railway alarm system in Japan. Since the operation of the Bullet Train started in 1964, an automatic system to stop or slow down trains during strong earthquakes has been developed [136], which has become the best known example of an earthquake and tsunami early-warning system in the world [137]. The Meteorological Agency has long been engaged in routine seismological observations. Earthquake information can be released quickly to the public through cellular phone, television, radio and local-community speaker system (see Fig. 15). Its earthquake early-warning system was upgraded in 2007 and has since provided more than 10 warnings of strong earthquakes. The system detected the earthquake off the Pacific coast of Tohoku about 8 s after the first wave arrived at the closest seismic station, and issued an immediate warning to the public in the region close to the epicenter. Twenty seven bullet trains automatically stopped without derailments in this region. Three minutes later, warnings for very large tsunamis were issued to Iwate, Miyagi and Fukushima prefectures. The damaging waves arrived 15–20 min later at the closest shores [58]. Why was not such an elaborate tsunami warning system adopted by TEPCO at the Fukushima Daiichi NPP?

Second, with a relatively comprehensive legal system, why did not Japan's nuclear watchdog compel TEPCO to upgrade countermeasures against tsunamis at the Fukushima Daiichi NPP? Japan has developed a regulatory framework for nuclear safety, according to the standards of IAEA. At the top of the framework, the *Atomic Energy Basic Act*, enacted in 1955, outlines the basic philosophy for utilization of nuclear energy. The *Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors* enacted in 1957 defines the responsibility of the government to regulate nuclear safety and the obligations of nuclear operators to abide by the regulations. The *Law for Prevention of*

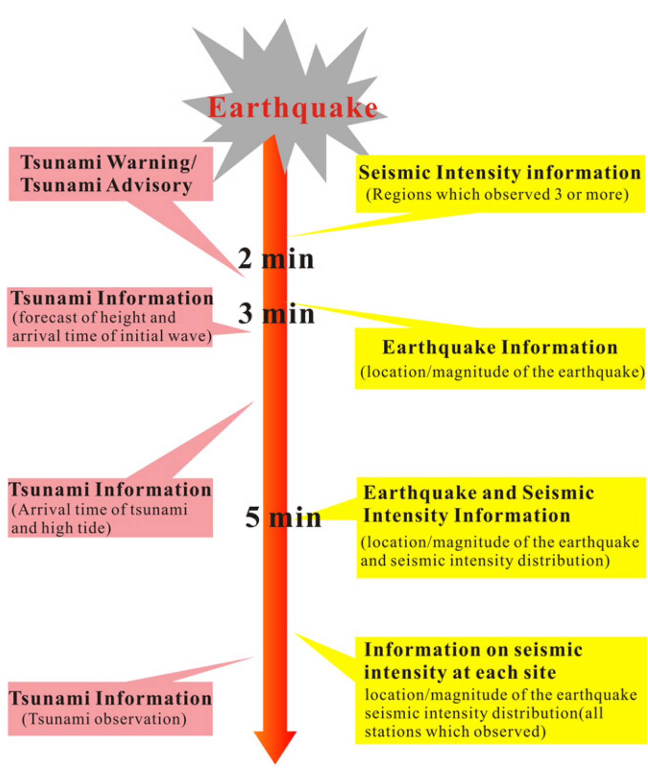


Fig. 15. Flow of issuance of information about tsunami and earthquake.
Sources: [118].

Radiation Hazards due to Radioisotopes, etc., the *Electricity Business Act*, and the *Act on Special Measures Concerning Nuclear Emergency*, among others, have all been put in place [2] (see Fig. 16).

Notes: (i). The *Atomic Energy Basic* Act stipulates the basic policy of utilizing nuclear energy in Japan. (ii). The *Reactor Regulation Act* stipulates, for commercial power reactors, the procedures for safety regulation and the licensing criteria for the permission of establishing a reactor, approval of operational safety regulations, operational safety inspection and decommissioning of a reactor, among others, as regulations necessary for the establishment and operation of a reactor. The act also provides for dispositions such as suspension of operation and license revocation and criminal punishment including imprisonment and fine. The Ministerial Ordinances and other regulations established under the Reactor Regulation Act are the "Rules for Commercial Nuclear Power Reactors concerning the Installation, Operation, etc." and the "Notice on Dose Limits". (iii). The *Electricity Business Act* provides for the procedures for safety regulation, including approval of design and construction method, pre-service inspection and facility periodic inspection for commercial power reactors. The Ministerial Ordinances and other regulations, established under the *Electricity Business Act* and related to the safety regulation on nuclear installation, are the *Rules for the Electricity Business*, the *Ordinance of Establishing Technical Requirements for Nuclear Power Generation*, the *Ordinance of Establishing Technical Requirements on Nuclear Fuel Material for Power Generation* and the *Technical Requirements on Dose Equivalent*, etc. [2].

Nuclear safety laws and regulations are implemented stepwise from the preparation phase of constructing nuclear power stations to the operation phase (see Fig. 17). In addition to NISA's monitoring, NSC implements and double-checks in each phase.

Finally, with an emergency response system in place, why was the decision to inject seawater to reactors delayed for 14 h and 9 min? Japan has established a relatively comprehensive nuclear emergency response system. The Nuclear Emergency Preparedness Act was adopted after the criticality accident in 1999 at nuclear fuel fabrication facilities of Japan Nuclear Fuel Conversion Co. This act specifies nuclear operators' duties on prevention of nuclear disaster, and implementation of emergency response measures, measures for restoration from nuclear emergencies, etc. The Act outlines the organizational structure and responsibilities of government agencies and nuclear operators. The act also clearly stipulates the emergency procedure as followed (see Fig. 18):

1) The nuclear operator must immediately report to the Ministry of Economy, Trade and Industry (METI) and heads of local governments when an event stipulated in Article 10 of the Nuclear Emergency Preparedness Act (Specific Event) occurs.
2) METI, receiving the notification, shall trigger activities according to the procedure stipulated by law. The Senior Specialists for Nuclear Emergency Preparedness assigned to work on-site shall collect information and perform duties necessary to smoothly implement the prevention of the expansion of a nuclear disaster.
3) When the Minister of METI recognizes that the Specific Event has exceeded the predetermined level and developed into a nuclear emergency situation, the Minister shall immediately report it to the Prime Minister.
4) The Prime Minister shall declare "Nuclear Emergency Situation" in response to it and direct relevant local governments to take emergency response measures such as sheltering or evacuation and preventive stable iodine administration.
5) The Prime Minister shall establish a Nuclear Emergency Response Headquarters in Tokyo.
6) In a nuclear emergency, NSC shall convene the "Technical Advisory Organization in an Emergency" that is composed of

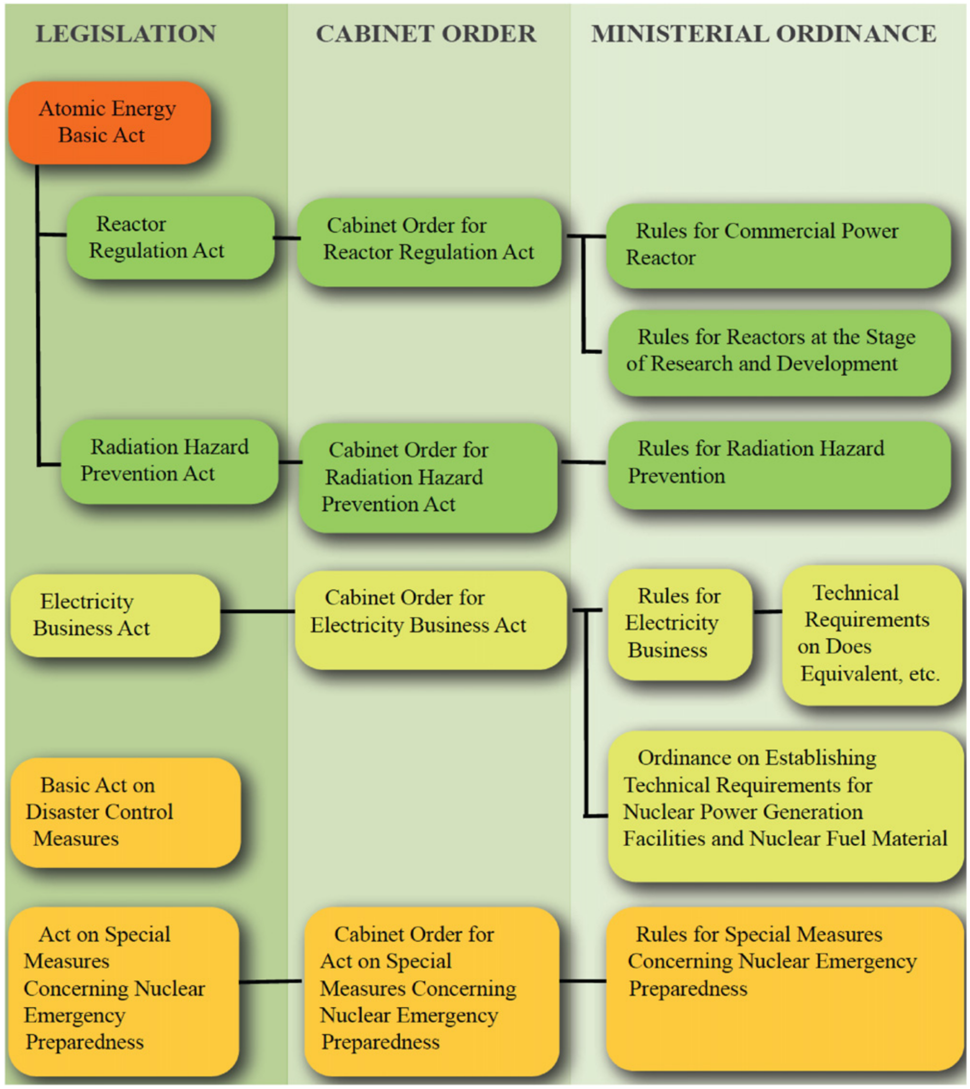


Fig. 16. Main legal structure of safety of nuclear facilities in Japan. *Notes*: (i). The *Atomic Energy Basic* Act stipulates the basic policy of utilizing nuclear energy in Japan. (ii). The *Reactor Regulation Act* stipulates, for commercial power reactors, the procedures for safety regulation and the licensing criteria for the permission of establishing a reactor, approval of operational safety regulations, operational safety inspection and decommissioning of a reactor, among others, as regulations necessary for the establishment and operation of a reactor. The act also provides for dispositions such as suspension of operation and license revocation and criminal punishment including imprisonment and fine. The Ministerial Ordinances and other regulations established under the Reactor Regulation Act are the "Rules for Commercial Nuclear Power Reactors concerning the Installation, Operation, etc." and the "Notice on Dose Limits". (iii). The *Electricity Business Act* provides for the procedures for safety regulation, including approval of design and construction method, pre-service inspection and facility periodic inspection for commercial power reactors. The Ministerial Ordinances and other regulations, established under the *Electricity Business Act* and related to the safety regulation on nuclear installation, are the *Rules for the Electricity Business*, the *Ordinance of Establishing Technical Requirements for Nuclear Power Generation*", the *Ordinance of Establishing Technical Requirements on Nuclear Fuel Material for Power Generation* and the *Technical Requirements on Dose Equivalent*, etc. [2].
Sources: [2,73].

the Commissioners and the Advisors for Emergency Response and shall give technical advice to the Prime Minister [2].

6. Root cause: nuclear regulatory failures

We argue that the root cause of the problems is the failure of the Japan's nuclear regulatory system. This argument is in line with those who believe the Japan's nuclear regulatory failures contributed to the Fukushima nuclear accident [1,2,13,16,17,20,21,46,47,49,62,67,73]. Both nuclear regulators and nuclear operators were far too lax with the regulations on operation and development of nuclear facilities and complacent with the safety record of nuclear power plants. For example, when asked why the government failed to act on tsunami warnings, Mr. Banri Kaieda, the minister of METI, said his ministry had blindly believed Japan's nuclear plants "were the safest in the world" [140].

6.1. Japan's regulatory culture—from "Japan Inc." to "nuclear village"

Confucianism has had significant influence on Japan's society and economy, even though the country has modernized and industrialized [141,142]. It has also historically shaped the Japanese regulatory culture [143,144]. With the influence of Confucianism, bureaucrats tend to see themselves as samurai and the businesses as serfs. And businesses voluntarily look to the government for guidance and defer decisions to politicians. These attitudes, coupled with the view of the nation as a family, have nurtured a close tie between government and business, the

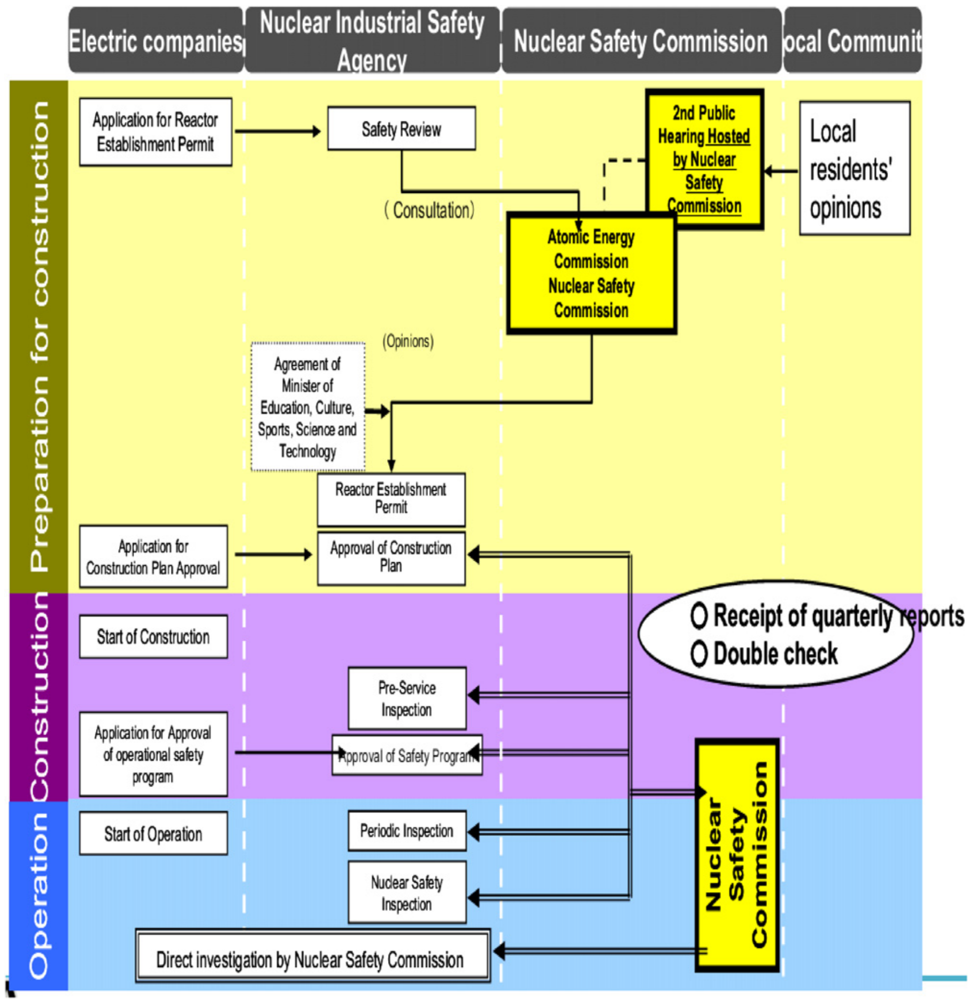


Fig. 17. Overall structure of implementing nuclear safety regulation in Japan.
Source: [139].

so-called "Old Boy" network [125]. Businesses worked hard not only for their shareholders but also for the targets set by government [142,143,145]. "Japan Inc." has been used by the western observers to describe the shared interests between government and business [146]. Some question whether "Japan Inc." is still a correct description of Japan after it underwent a series of reforms in the 1990s. Others insist that this unique and close relationship shaped the development of capitalism in Japan rather than the western model of capitalism [147–150].

"Nuclear village" is used to describe the "Japan Inc." in the nuclear industry [15,78,88,97–99,116,151]. The term "nuclear village" ("genshiryoku mura," 原子力村, in Japanese) first appeared in an opinion piece in a magazine in 1997. It refers to a small, closed community of interests that spread its influence through political, economic and academic interests to promote nuclear energy in Japan. This "nuclear village" emerged in the early 1970s when the world oil crisis triggered great interests in nuclear energy in Japan where calls were made to promote atomic energy to reduce the country's heavy reliance on imported fuel [78,97]. In the "nuclear village", the like-minded – nuclear operators and bureaucrats – have prospered by rewarding one another with construction projects, lucrative positions, and financial and political support [15,78,99,116].

"Nuclear village," so entrenched in the Japanese political and business world, easily survived the political shake-ups of the last two decades. When the Democratic Party came to power in 2009, it pledged to reform the nuclear industry and strengthen the NISA. But soon the reform evaporated quietly. While moves to strengthen oversight were put on the back burner, the government announced a new nuclear expansion plan in 2010, which included building 14 new reactors by 2030 to increase the share of electricity generated by nuclear power and other renewables from 34 to 70 percent. The "nuclear village" was further strengthened when the government decided Japan should become a nuclear exporter, selling nuclear reactors and technology to energy-hungry developing countries. This would be a central component of a long-term export strategy. A new company, the International Nuclear Energy Development of Japan, was created to do just that. The government took a 10 percent stake. TEPCO took the largest stake, with 20 percent, and one of its top executives was named the company's first president [116].

Transparency and public involvement is an absolute condition to avoid regulatory failures [152–154]. However, the "nuclear village" discouraged public participation in Japan's nuclear policy making process [72]. Indeed, in the nuclear accident at Fukushima Daiichi NPP, the Japanese government and TEPCO received numerous complaints about their uninformative public releases [81,83,155]. On July 29, 2011, Yukiya Amano, Director General of IAEA, a Japanese national himself, openly criticized TEPCO because "*sufficient information failed to reach the IAEA in the initial phase of the accident*" [101]. On July 4, 2011, the Atomic Energy

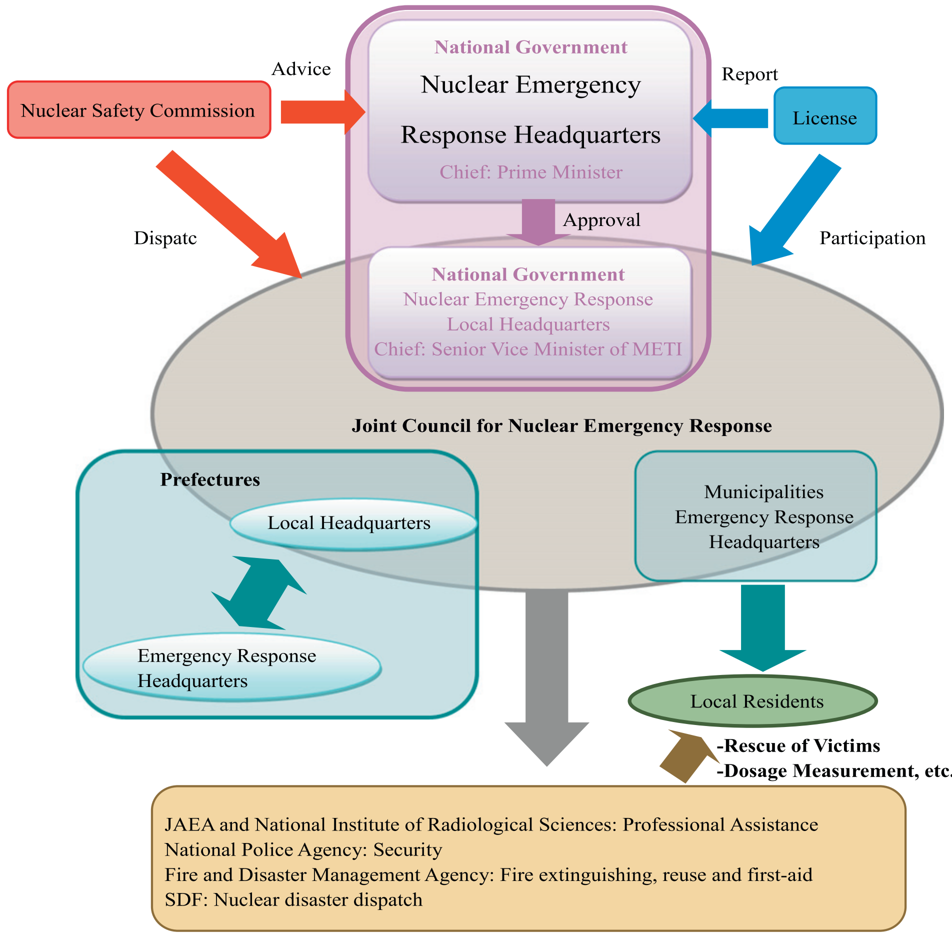


Fig. 18. Outline of the organizations relating to nuclear emergency responses.
Source: [2].

Society of Japan, a group of nuclear scholars and industry executives, expressed the same complaints, "…this sort of important information (radiation monitoring) was not released to the public until three months after the fact." [83].

6.2. Nuclear regulatory agency— promoter and regulator of conflicts

The cozy relationship between government and business in Japan worked in many ways and through numerous channels for the interests of the nuclear industry. A key connection of the "Nuclear village" to government is METI, the successor of the Ministry of International Trade and Industry (MITI). METI has jurisdiction over broad policy areas, including industry policy and energy policy [148]. The Japanese nuclear regulatory body, NISA is a division of METI. This is often argued to be the main reason for regulatory capture.

In Japan, there are three nuclear organizations: Japan Atomic Energy Commission (AEC), NSC and NISA. NISA dominated Japan's nuclear regulating system [1,2] (see Fig. 19). As a division of METI, NISA has multiple and seemingly conflicting roles. NISA is supposed to promote nuclear industry and regulate it too. In practice, NISA and the nuclear industry share many interests in promoting nuclear power as a carbon-free energy source. It has long been argued that regulators should be independent from other government agencies to be able to work effectively (136). In the 1970s, the United States split these two functions: U.S. Department of Energy promotes nuclear power while the U.S. Nuclear Regulatory Commission (NRC) regulates the industry, including nuclear safety [156]. France separated these functions by removing its nuclear regulator from the government bureaucracy and granting it an independent authority [157].

Some argue that NISA failed to act as a watchdog for nuclear safety, protecting the public interest to ensure safe operation of nuclear reactors. NISA did carry out plant inspections once every 13 months and check safety measures every quarter. Yet, there were no surprise inspections [158,159]. Worse still, NISA relied on the nuclear industry to develop proposals and rules, which reflected more the demand of the nuclear industry than nuclear safety requirements [88,116,117,160]. In the most serious case, as mentioned earlier, TEPCO acted as ventriloquist—it had told NISA that sea waves would not exceed 5.7 m at Fukushima site in a safety guideline submitted in 2002. NISA then approved the Fukushima Daiichi nuclear plant designed to withstand 5.7 m sea waves. On March 11, 2011, the water reached 14 m above sea level, inundated the plant, cut off electricity supplies, destroyed back-up generators for the cooling system of the reactor, and caused the nuclear disaster [88].

Others point out theproblems of nuclear regulatory capture in Japan where regulators/law makers and the regulated nuclear operators had developed a mutually beneficial relationship. As members of the nuclear community, regulators sought profits from the nuclear industry while nuclear operators received favorable policies in return [17,72,73,116]. NISA had nurtured a public myth of "absolute safety" of nuclear power. For example, in 2010, when Niigata Prefecture planned to conduct an accident drill for earthquake preparedness, NISA recommended revising

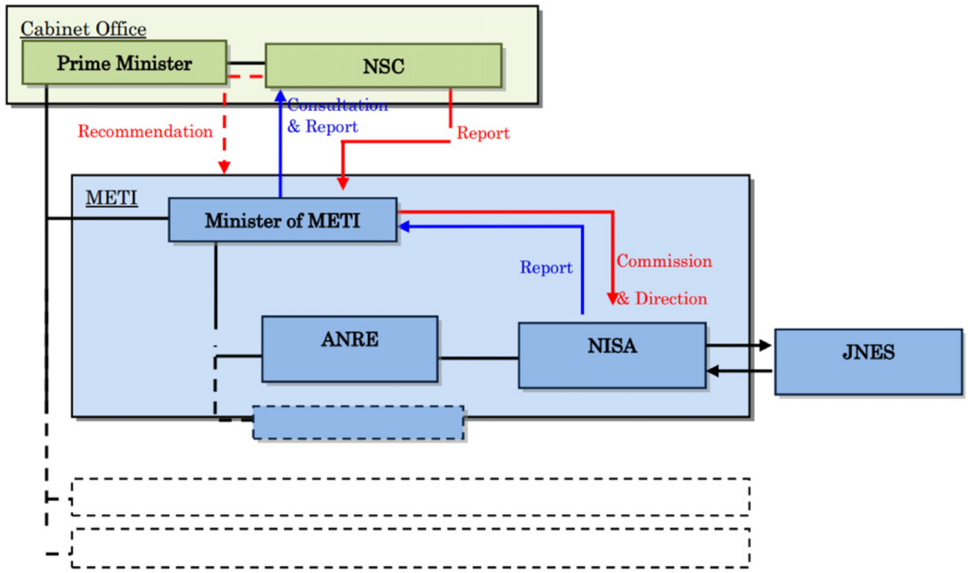


Fig. 19. Position of NISA in the Japan's nuclear regulatory bodies.
Source: [2].

the plan to avoid sparking "unnecessary misunderstanding and anxiety" in the public; the prefecture was duly obliged to drop the earthquake premise in favor of a less menacing alternative—heavy snowfall! [161].

Although this system of having promoters and regulators under the same roof had been criticized for years, no administration had been ready or even keen to separate them before the Fukushima nuclear disaster [88,116,160].

6.3. Corruption becomes a widespread practice in Japan's nuclear industry

A 'revolving door' between amakudari (descend from heaven) and amaagari (ascent to heaven) leads to corruption as it provides a strong incentive for bureaucrats to relax regulation [162,163]. Regulatory failure is almost inevitable if corruption is not averted or effectively controlled [164]. Unfortunately, no industry is perhaps as rife with amakudari and amaagari as the nuclear power sector in Japan [72]. Amakudari and amaagari have become widespread practice between the Japanese government agency and companies [147,148]. Amakudari allows Japanese bureaucrats to retire to high-profile positions at nuclear companies they once oversaw, whereas amaagari allows Japanese nuclear regulatory agencies to hire freely experts or others from nuclear utilities [145,147].

Amakudari: Toru Ishida became an adviser at TEPCO in January, 2011, less than six months after retiring as the head of the Agency for Natural Resources and Energy, an agency that is supposed to promote the nuclear industry [116]. Generally, after retirement, senior government officials went to work at large nuclear utilities as executive board members, advisers or even vice presidents, whereas those of lower ranks ended up at smaller utilities in a pattern reflective of the rigid hierarchy in Japan. When a senior official retires from a nuclear company, his junior counterpart at the regulation agency would take over the position as the agency's "reserved seat" at the company [73,116,159,165]. There were frequent movements of officials between government agencies and nuclear power companies. According to the investigation by *The Yomiuri Shimbun*, since 2000, 68 former ministry officials were parachuted into post-retirement jobs at 12 of the country's power companies [97]. At TEPCO, between 1959 and 2010, four former most senior officials from government ministries and agencies served as vice presidents [94]. As of May 2, 2011, there were still 13 former industry ministry officials working at TEPCO and 10 at other power companies [97].

Amaagari: Nuclear companies deepened the relations with the government and bureaucracies by temporarily dispatching employees to government bodies. Since 2000, "power companies sent at least 100 employees to cenral government bodies for on-loan postings" and TEPCO alone sent 32 to take on the de facto 'reserved seat at government agencies' [97]. These government bodies include NSC and other offices involved in safety regulation. NISA alone accepted 80 on-loan employees of utilities and other nuclear-related firms. One former Toshiba employee served as a safety inspector at the Fukushima Daiichi NPP, which used Toshiba-made reactors [97]. Again, Associated Press examined the business and institutional ties of 95 people currently at three main nuclear regulatory bodies (NISA, AEC, and NSC). Overall, 26 of them were affiliated either with the industry or groups that promote nuclear power, typically with government funding. AP also came across 24 people with prior positions at those three regulatory bodies—one-third of whom had connections with the industry or pro-nuclear groups [88].

The 'best' example of this practice of *amakudari* and *amaagari* probably is the career of Mr. Tokio Kano. Mr. Kano joined TEPCO in 1957, became a leader in its nuclear unit in 1989. In 1998, he entered the Japanese parliament as a candidate for a seat given to the nation's largest business lobbying group—Keidanren, of which TEPCO is one of the largest members. Backed by Keidanren, Mr. Kano served two six-year terms in the upper house of the Parliament until 2010. In parliament, Mr. Kano led a campaign to reshape the country's energy policy by putting nuclear power at its center. In 2003, with Mr. Kano's leadership, Japan adopted a national energy plan calling for the expansion of nuclear energy as a way to achieve greater energy independence and to reduce Japan's emission of greenhouses gases. The plan and subsequent versions mentioned only in broad terms the importance of nuclear safety despite the 2002 disclosure of cover-ups of an accident at Fukushima Daiichi and an accident in 1999 at a plant northeast of Tokyo where high levels of radiation were leaked into the air. In July 2010, in a move that has raised eyebrows even in a world of cross-fertilizing interests, Mr. Kano has returned to TEPCO as an adviser [73,116,159,165].

7. Concluding remarks and policy recommendation

7.1. The Fukushima accident could have been averted with effective regulation

There were some serious problems with the nuclear safety regulatory system in Japan over the last three decades—nuclear regulators pretended to regulate; nuclear utilities pretended to be regulated [14,15,17,72,73,88,115,116,159,161]. Collusion of interests was apparent.

TEPCO, the operator of the Fukushima Daiichi NPP, had a record of safety violations that stretched back decades. Mostly notably in 2002, TEPCO admitted that between 1997 and 2002, on some 200 occasions, maintenance reports on nuclear plants had been falsified [165,166]. This information initially had come from a whistleblower at GE, which helped build the plants and contracted with TEPCO on operational matters for decades. Maximum fines for providing fraudulent documentation were up to 100 million yen ($1.3 million). However, no such a penalty was imposed on any utilities, not even TEPCO which had openly admitted to providing falsified records. What TEPCO did do in 2002 was to fire four top executives in the name of getting its house cleaned. Yet, three of the four fired top executives later took jobs at companies that conducted business with TEPCO [17,88,116].

Fukushima Daiichi NPP was rated one of the five worst nuclear power plants in the world between 2004 and 2008 [167] and one of the most trouble-prone nuclear facilities in Japan in the last decade [82,168]. In a recent case, in August 2010, employees at the Fukushima power plant were supposed to work on the unit 6 reactor, but instead began conducting work on the unit 5 reactor. Their altered work on their own led to a mistake that rendered the unit's cooling system inoperable [73,82]. Nonetheless, NISA granted unit 1 reactor an extension of 10 years after its 40-year lifespan just days before the earthquake and tsunami on February 7, 2011, despite the high risks of its old model of reactor and poor records of operation and management [169]. This 'radical' approval for extension later contributed to the fatal decision not to inject seawater right away.

Eisaku Sato, the governor of Fukushima Prefecture from 1988 to 2006, told the *New York Times* that an organization that was inherently untrustworthy could be put in charge with ensuring the safety of Japan's nuclear plants clearly shows that "the problem is not limited to TEPCO, which has a long history of cover-ups, but it's the whole system that is flawed" [170].

Based on available information from official reports, academic papers, and news analysis, we argue that the worst nuclear accident since Chernobyl probably could have been averted under an effective nuclear regulatory system.

7.2. Upgrading the nuclear regulatory system

Nuclear accidents like Fukushima one would be considered unlikely in a country with effective nuclear safety regulation. Drawing lessons from the Fukushima nuclear accident and upgrading and strengthening the nuclear regulatory regime is not optional but imperative in all countries that have or are planning to have nuclear energy programs, a regulatory regime which consists of an organizational structure that ensures the independence of regulators from policy makers and the businesses they are supposed to regulate, an operational legal system that can ensure regulations will be implemented; human capacities to conduct regulation and monitoring, to a culture that respects rules and regulations.

The exclusive and closed "nuclear village" in Japan reminds us that regulatory transparency is an absolute condition for any effective nuclear regulatory system [72]. To ensure regulatory transparency, the government needs to make available not only general information on how nuclear energy can be and is used for peaceful purposes, but also specific information on siting, reactor models, their operation and how spent fuel is managed. Information can be made available through traditional channels, such as government reports and studies. It can also be disseminated through the internet, which increasingly contributes to making the regulatory system transparent and accountable around the world [171,172]. The internet provides a platform where individual from all walks of life can launch public debates concerning nuclear issues [67,173]. Public involvement and awareness are important for regulatory transparency and effectiveness.

We also suggest all countries with civilian nuclear energy programs should make an immediate in-depth review of the country's regulatory system. A credible nuclear watchdog must be an independent agency. NISA was a victim itself in part because of its combined role as both industry promoter and industry regulator, which seriously undermined its capacity as a nuclear safety watchdog. Since the worst nuclear accident at Chernobyl, many countries have already created independent nuclear regulatory agencies. Yet to make them truly independent, the practice of 'revolving doors' between nuclear regulatory agency and nuclear utilities should be limited to the minimum. Given the nature of nuclear energy (highly technical complexities and small groups of people having the knowledge and expertise), the mobility of its professionals is limited in a broader world while their mobility in the field, particularly between government agencies and industries, is much greater [85,174]. Regulations and rules need to be put in place to prevent collusion of interests.

Finally, international cooperation is needed to improve nuclear safety regulation and practice. Wider and Deeper International Cooperation includes but is not limited to:

(i) Higher international safety standards should be adopted by countries wishing to have nuclear energy programs, and incorporated into their domestic legislations and regulations. These standards should particularly include provisions covering better preparedness for disasters such as floods and earthquakes, as well as for any events that cause a prolonged loss of electrical power, the key factor that led to the Fukushima disasters [19].

(ii) Countries need to grant IAEA more authority to act as an international nuclear watchdog, not only over nuclear proliferation issues, but also civilian nuclear safety. IAEA should be allowed by its members to monitor the implementation of international rules and regulations on civil nuclear programs, to conduct independent inspections on nuclear power safety if it deems necessary under with the Incident Reporting System (IRS). Strengthening IAEA's role in civilian nuclear safety also requires budgetary and other financial resources and human capacities too [66,175]. The budget of IAEA for 2011 was €314 million (plus $70.4 million voluntary contribution), of which 10% was for nuclear safety and security (IAEA 2012). Compared with other international organizations, IAEA is small in size as well as in operation [66,176].

(iii) G2 (U.S. and China) should take a leadership role [73]. The United States has 104 reactors in operation, making the country the world's largest nuclear energy producer. China currently has 26 reactors under construction (as of January 2012), representing over 40% of the global total [34]. Meanwhile, China is building the first Westinghouse AP1000 under the technology transfer agreement. The two countries should jointly develop the safety standard for the third generation of reactors, which include improved fuel technology, superior thermal efficiency, passive safety systems and standardized design for reduced maintenance and capital costs [177,178].

US–China Strategic and Economic Dialog can facilitate this cooperation on nuclear safety regulation [73].

We live in a nuclear world. 436 reactors in operation in 30 countries (until January 2012) provide about 13 percent of the world's electricity production [35,45]. Meanwhile, there are 63 new reactors under construction in 14 countries [45]. However, a nuclear accident knows no boundaries. In such a dangerous world, a high priority must be placed on efforts aimed at upgrading and enhancing nuclear safety regulatory system. With effective nuclear regulatory system, nuclear accident like the Fukushima can be prevented.

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